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Physics of Boundaries and Their Interactions in Space Plasmas

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Highlights of Work

In the following, we provide a summary of our most significant research accomplishments during the first two years of funding. For the sake of brevity, most of the projects are explained in a paragraph length, highlighting only pertinent results.

Magnetopause

It is well known that the magnetopause plays a central role in the energy and particle transfer of the shocked solar wind into the magnetosphere. One of the primary processes mediating this interaction is that of dayside reconnection. In addition, viscous coupling via wave-particle processes (e.g., Kelvin-Helmholtz instability, KH) is an alternative means of energy exchange and mixing between the magnetosheath and magnetospheric plasmas. Our objective was to study these processes as they occur during southward IMF, and how they modify the structure of the magnetopause and its boundary layer(s).

First, we addressed the fundamental question of how reconnection takes place at the kinetic level. While almost all resistive MHD and ion-kinetic models assume that the tearing instability underlies magnetopause reconnection, theories of tearing predicted very small saturation amplitudes, making it very unlikely. Using 2-D, high-resolution full-particle simulations, we studied the evolution of the magnetopause current layer as a function of rotation of the magnetic field. We found that the tearing mode, even for field configurations far from being antiparallel, has fast growth rates and saturates at sufficiently large amplitudes to account for the formation of flux transfer events (FTEs) in the magnetopause. We also developed a new nonlinear theory for the saturation of the tearing mode that correctly predicts the amplitudes seen in the simulations.

Having thus established a good footing for the standard assumption in ion-kinetic (hybrid) simulations, that the tearing instability underlies the reconnection process and the formation of plasmoids (FTEs), we proceeded to investigate the magnetopause with a variety of 2-D and 3-D simulations. At the local level, we established that KH instability is much more important, and more intimately tied to reconnection, than previously thought. We found that the drift between current-carrying ion species and ions of the surrounding sheath and magnetosphere will make the current sheet unstable to KH in a large range of circumstances. In contrast to conventional KH instability, which is driven by the sheath flow, this new instability also operates close to the subsolar point. The significance of this type of KH is that it sets a lower limit on the magnetosheath thickness, strongly interacts with tearing (allowing for more flux to connect), and leads to significant enhancements of the plasmoid core field.

In general, flux ropes are 3-D structures, and as part of the large-scale reconnection configuration, require inflow/outflow simulations. We have summarized some of our results in Plate 1. These simulations employ the kinetic equivalent of the open, floating boundary conditions. Any inflow or outflow is self-consistently generated by the reconnection process and is not imposed from the outside. Plate 1 shows a flux transfer event (FTE) formed on the magnetosheath side at two different view angles. In both cases, the magnetosheath is on the left and the magnetosphere is on the right. Such FTEs manifest themselves as bubbles (depressions) on the magnetosheath (magnetospheric) side of the surface of the magnetopause. While regardless of the size of the guide field, the plasmoid bulges almost entirely into the magnetosheath (due to the strong B field in the magnetosphere), it is only for a finite guide field that the plasmoid detaches to form a fluxrope. We also note from the simulations that in the presence of a finite guide field,

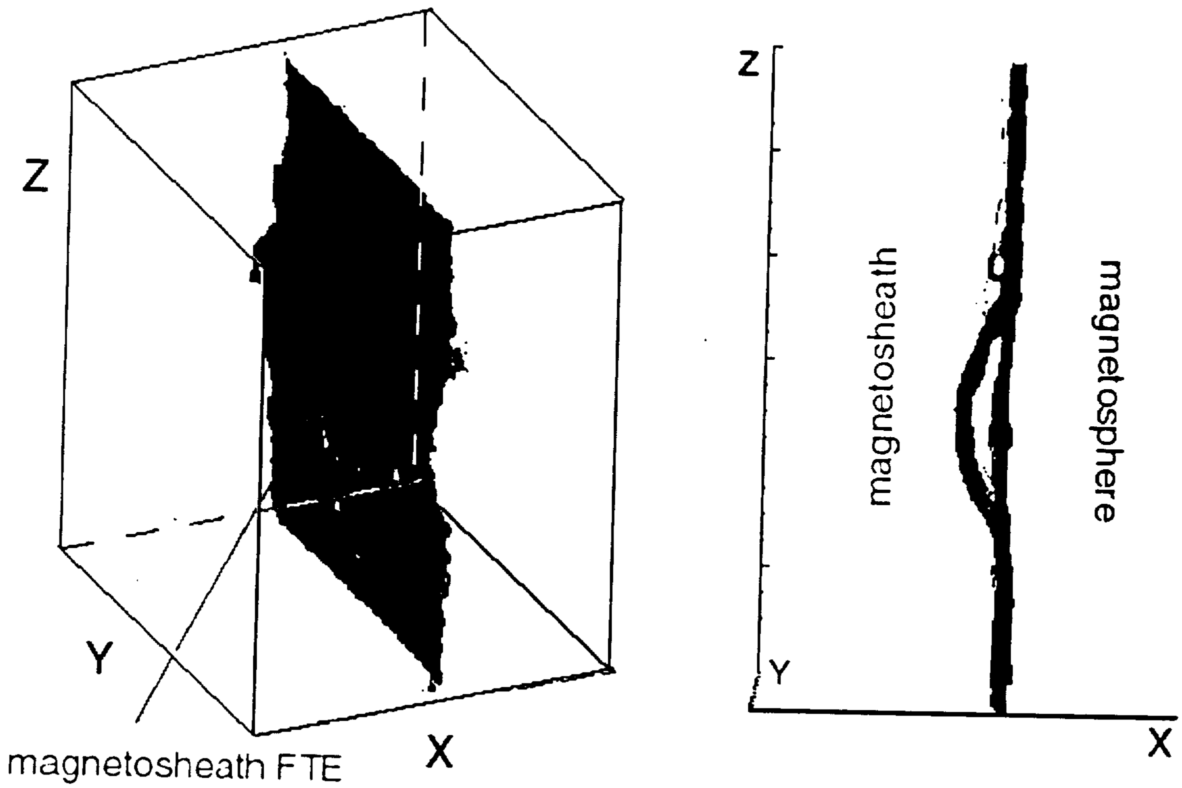

Plate 1. Formation of a magnetosheath FTE in a 3-D hybrid simulation of the magnetopause. A flux rope initially appears as a blister or a bubble on the surface of the magnetopause but unlike a plasmoid, it detaches from this surface. This effect is demonstrated through two viewing angles of an isosurface of $|B_y|$, where y is in the direction of the main component of the field.

3-D effects cause the reconnection process to be cut-off temporarily, leading to intermittent reconnection. We are currently investigating whether this intermittence can explain the observed occurrence rates and sizes of FTEs. Finally, the strong coupling between the guide field and the Hall-induced field results in a fluxrope structure with very large core fields and can explain the ubiquitous observations of such high fields in FTEs. This is in spite of the high plasma beta of the magnetosheath which acts to suppress the core field generation.

We have also investigated the structure of the magnetopause during periods of southward IMF using planar and curved geometries in 2-D hybrid simulations. In the planar geometry, the structure of the magnetopause during steady reconnection (i.e., a single X line) was investigated. The results showed a structure consisting of multiple discontinuities/boundaries, none of which could be matched with a classical fluid discontinuity such as a rotational discontinuity. The causes and degree of prevalence of such structures is under investigation. Similar results where also observed in the curved geometry where multiple X lines and plasmoids with varying sizes were formed. In this case, however, the lack of the usual discontinuities could be attributed to the presence of multiple plasmoids at the magnetopause which result in a magnetic field topology quite different from that of a single X-line reconnection. The presence of plasmoids also gives rise to a considerable variation in magnetopause thickness as a function of latitude. This variation was found not to be symmetric with respect to the magnetic equator nor was it found to be a monotonically increasing or decreasing function of magnetic latitude.

Magnetotail

In addition to research that directly addresses the energy release processes during substorms, the question of the overall structure and dynamics of the magnetotail is an important research topic. Some of the outstanding issues that we addressed were in regards to the formation of the plasmasheet boundary layer (PSBL) and the population of the central plasma sheet (CPS). Slow shocks, which may bound the reconnection region, are the prime mechanism for plasma entry into the CPS, energization of ions, and formation of ion beams.

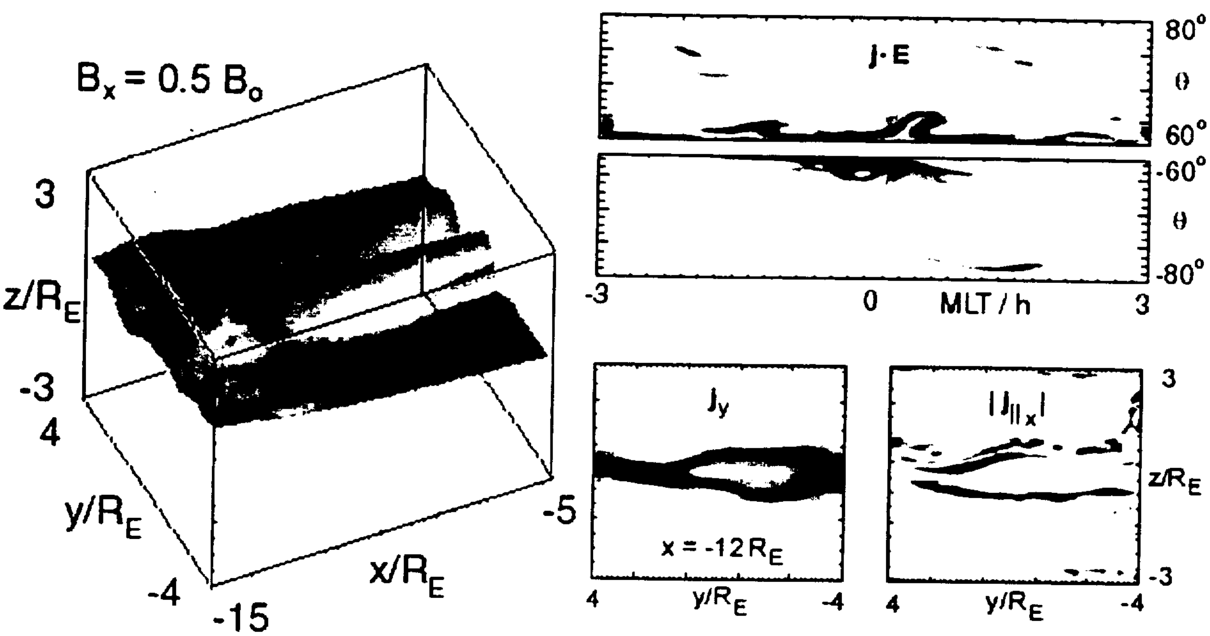

Plate 2. Left panel: Isosurface of the main field component B_x at 1/2 of its lobe value in our 3-D tail simulation, showing the modulation of the current sheet due to reconection and KH. Top right panel: associated ohmic heating in the ionosphere. Bottom right panels: y-z cuts of the cross-tail current j_y and the parallel current, at x = 12 R_E. The current is diverted around the thickening CPS and only partially converted into $j_{||}$ (plot intensity scale factor: 10) at the PSBL.

Over the past several years we have completed a substantial amount of work documenting the physics of slow shocks. Based on this work, slow shocks in the tail are expected to have a relatively large dissipation scale length of many tens to a few hundred of ion inertial lengths, and should be accompanied by backstreaming ions that generate Alfven waves. Slow shocks with just these characteristics have recently been observed by GEOTAIL. We found that ion thermalization at large shock normal angles is difficult to achieve due to the finite size of the CPS. As a consequence, ion distributions will typically be far from Maxwellian and can account for some of the observations of the crossing from the PSBL to the CPS. Kinetic effects and anisotropies also have a large impact on the phase velocities of low frequency modes and the ensuing ordering of the discontinuities in the flow. One of the more exciting possibilities resulting from this is a combined discontinuity made up of a slow shock and an RD. We demonstrated the existence of this coupled discontinuity with hybrid simulations. Shortly after our prediction, this new type of discontinuity was confirmed observationally in the tail. Slow shocks or slow shock-like discontinuities may also form more generally in the vicinity of major structures extending into the lobe, such as plasmoids. Taking a closer look at the plasmoids, we found that simultaneous reconnection from more than one X-line leads to a complicated "onion-shell" structure of interpenetrating ions (and associated B_y structure), which has recently been confirmed by GEOTAIL observations.

The dynamics and stability of the near-Earth tail are intimately related to thesubstorm onset. As a first step in exploring this connection, we investigated the effect of O^+ ions on the stability of the tail. Since it is known that ionospheric oxygen can make up a large fraction of the plasma (with increasing densities around substorm onset), one of the outstanding issues has been the role of O^+ in the substorm process. We showed that their curvature-drift-generated current only mildly affects the tail field configuration and reconnection rate, unless the O^+ beam parameters approach the marginal limit for firehose instability. However, there are many more ways in which O^+ can take part in substorm processes that remain to be investigated.

Many of the outstanding questions with regard to substorm onset are related to the respective roles of near-Earth current disruption mechanisms vs. NENL (near-Earth neutral line) reconnection, and the role of ionospheric coupling. To address these issues, we have performed the first 3-D ion kinetic simulations of the combined tearing (reconnection) and cross-tail instabilities of the near-Earth tail, demonstrating their respective ionospheric signatures. These large-scale, non-periodic inflow/outflow simulations allow us to study both the non-driven and driven aspects ofsubstorms. Similar to our results for the magnetopause above, we find that the near-Earth tail is unstable to KH. These simulations allow us to analyze the development of the current diversion, associated field aligned currents, and their ionospheric signatures. Plate 2 shows a snapshot of the 3-D current sheet (left panel), its ionospheric signature (top right panel), and an *x-z* cut demonstrating the (asymmetric) current diversion around the reconnection region. In this work, we have introduced ionospheric coupling by solving the ionospheric potential equation from the mapped magnetospheric parallel current, and by mapping the electric field back to the near-Earth boundary of the simulation. The significance of these types of simulations is that the crucial temporal evolution of physical quantities can be directly compared to both in situ and ionospheric observations, to help understand substorm dynamics and to distinguish between competing substorm models.

The planned extension of this work is to refine the description of the ionospheric coupling and the ring current, and to increase the simulation in all dimensions, such that the near and far tail are both included at once.

2.3 Global Simulations

Recent advances in computer technologies have allowed us to perform simulations that stretch from the upstream solar wind to the magnetotail regions. These simulations cover many aspects of the solar wind – magnetosphere interaction simultaneously, and enable us to look at all structures and boundary layers, and how they interact, as a whole. Our recent 2-D global hybrid simulations of solar wind interaction with a dipole magnetic field exemplify this major breakthrough. Plate 3 shows the ion temperature as a function of X and Y at the end of the simulation run. As the labels in the figure indicate, these simulations are able to capture the magnetosphere in considerable detail.

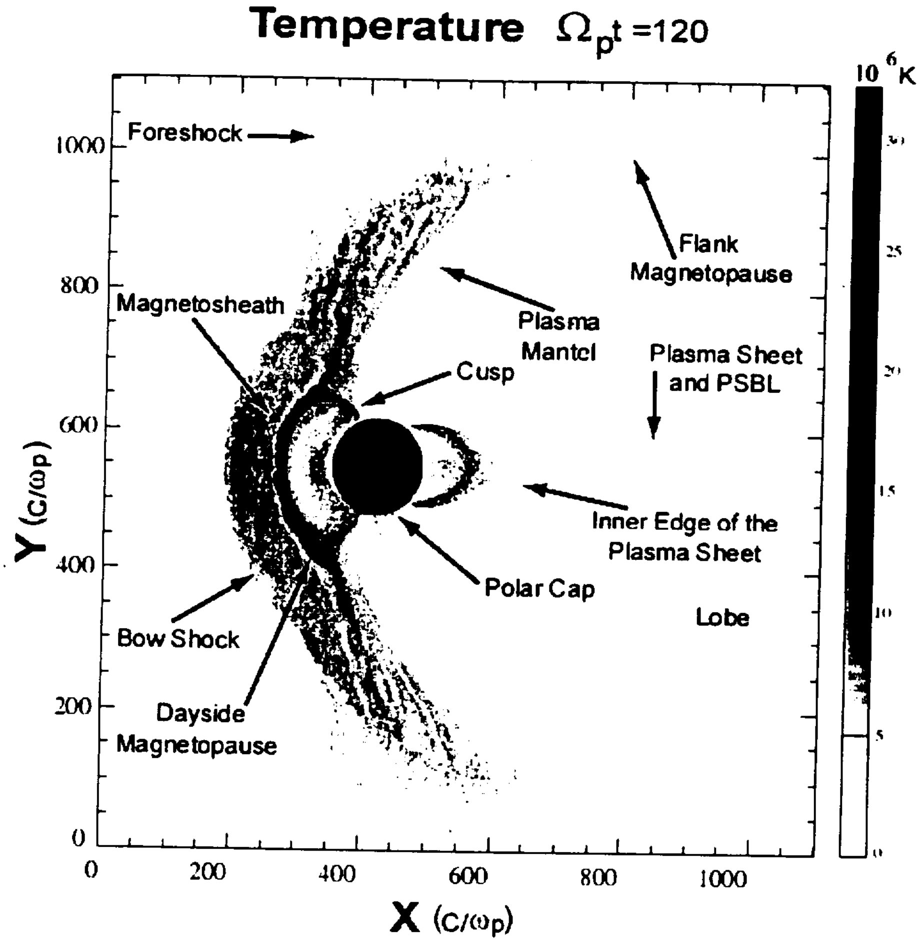

Plate 3. An intensity plot of the ion temperature as obtained from a 2-D global hybrid simulation of solar wind interacting with a dipole field during southward IMF.

Although global in nature, these simulations have a cell size of one ion inertial length and reproduce accurate kinetic physics on ion scales. As an example, the simulations reproduce the familiar plasma characteristics and associated ion thermalization at the quasi-perpendicular ($Q_\perp$) shock. However, these simulations also produce new physics on ion scales. An example that has escaped previous, local 1-D or 2-D simulations is the possibility of KH instability at the $Q_\perp$ portion of the shock. Plate 4 shows the ensuing filamentation and break-up of the shock surface. In simulations with the IMF mostly oriented in the dawn-dusk direction, a large velocity shear develops between the solar wind and the near-shock sheath flow. This can be seen in the left panel of Plate 4 that shows the y (northward/southward) component of velocity. This shear flow results in the Kelvin-Helmholtz instability that in the nonlinear regime gives rise to the filamentation of the shock and formation of a solitary band/filament, as evident in the right panel of Plate 4. The field and plasma signatures within this band are consistent with that of fast magnetosonic shock. However, except for a large diversion of the flow, the plasma behind the band has properties similar to that of the solar wind until a secondary shock front is encountered. As a result, the traversal of the shock filament and the secondary shock front resembles a multiple shock encounter except for the flow diversion behind the filament. Although single spacecraft measurements are capable of detecting (or may already have) the presence of such filamentation by virtue of its flow diversion, multi-spacecraft measurements such as the upcoming CLUSTER II mission are more suitable for detection of such structures.

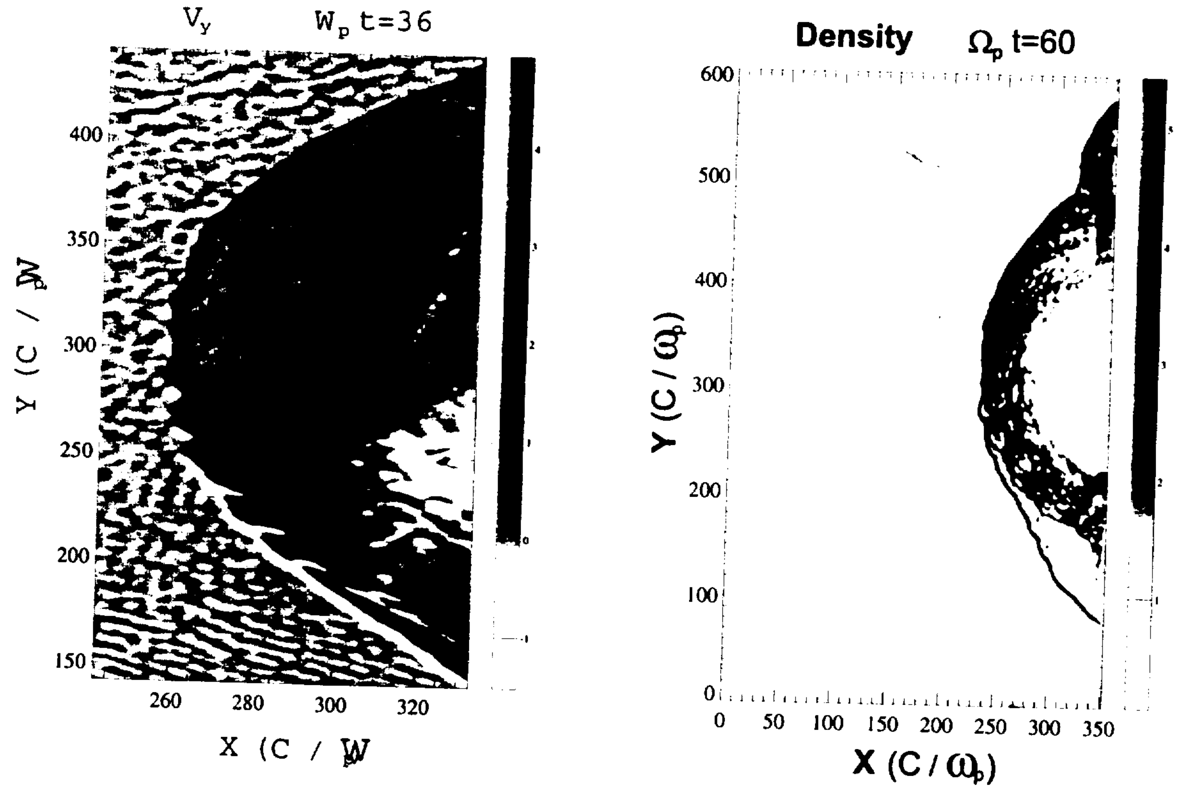

Plate 4. Intensity plots of ion density and Vy (northward velocity component) from a 2-D hybrid simulation of the curved bow shock. Bow shock is unstable to the Kelvin-Helmholtz instability (KH). Early in the simulation, the KH gives rise to modulations of the shock surface (left panel). As KH develops, part of the shock surface peels off, giving rise to a solitary structure as seen in the lower part of the right panel.

We emphasize that the most compelling aspect of these global kinetic simulations is the fact that the underlying physics down to ion temporal and spatial scales is correctly captured. This, together with the fact that by the right choice of plasma parameters we can ensure that the simulated plasmas have properties (e.g., density, flow velocity, temperature, and field strength) similar to the solar wind and magnetospheric regions, facilitates a direct comparison of results with spacecraft measurements. This is further illustrated in Plate 5. The top panel of Plate 5 shows an intensity plot of the total magnetic field strength with field lines superimposed on it while the bottom two panels show magnetic field and plasma parameters for cuts along the terminator and deep tail. Evidence for magnetic reconnection on the dayside can be inferred from the field lines. Also, modulation of the magnetopause surface (light region) due to multiple plasmoids can be seen. On the night side, both dipolar and highly stretched field lines are present with the X-line having just moved out of the simulation domain on the right hand boundary. The light region in the tail corresponds to the neutral sheet. The bottom two panels in Plate 5 clearly demonstrate the capabilities of these simulations to account for both global as well as local kinetic structure of various discontinuities and boundaries. For example, the cut along the terminator shows field and plasma fluctuations in the upstream followed by a rather broad and turbulent structure for the quasi-parallel shock. Further downstream, another transition associated with the magnetopause and boundary layer can be seen. Note that this layer is quite broad and considerably different from the subsolar magnetopause. This is due to the fact that here the transition is from the magnetosheath to the plasma mantel whose properties are similar to the magnetosheath and considerably different from the magnetospheric plasma near the subsolar magnetopause. The outer tail cut shows plasma and field variations

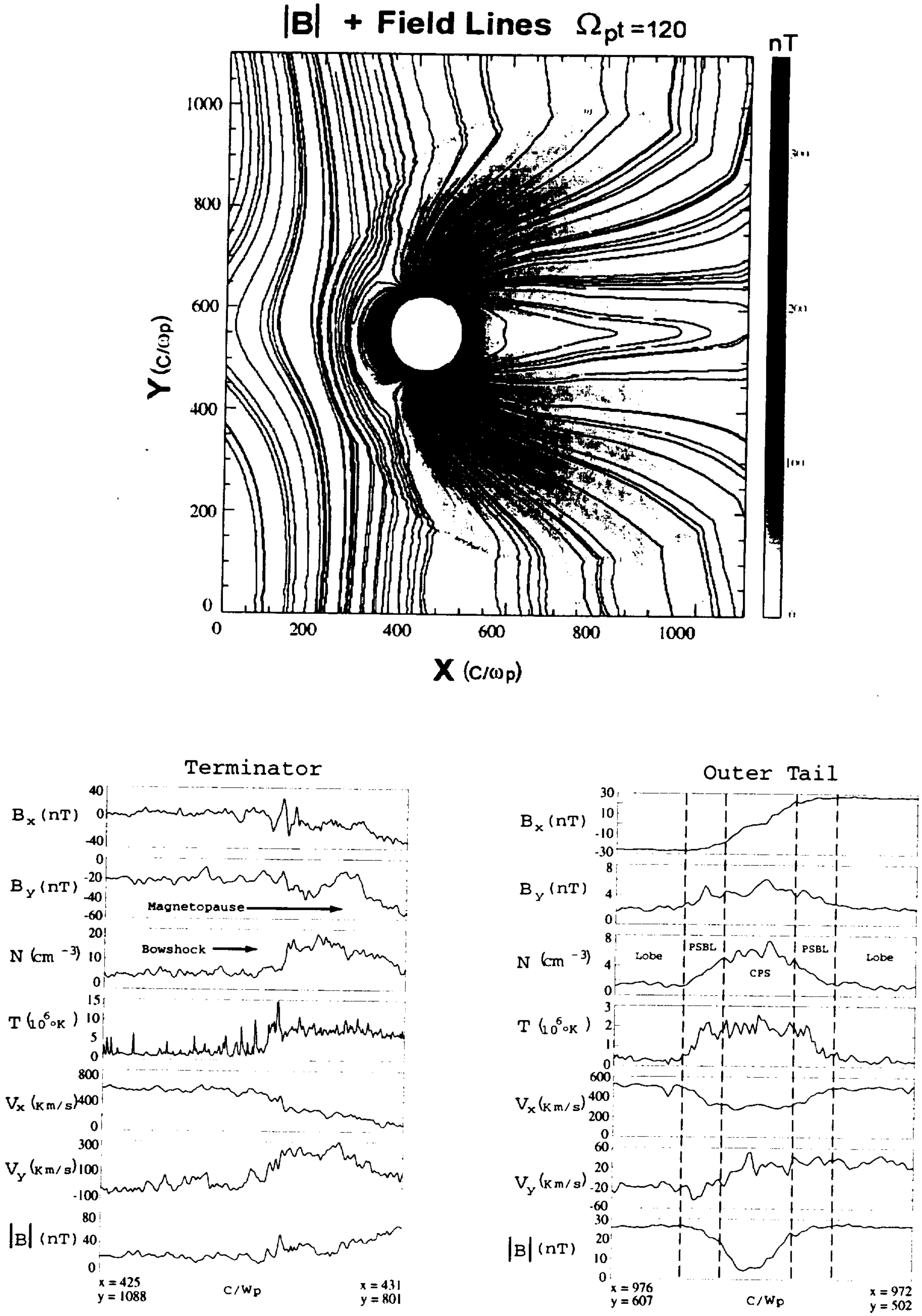

Plate 5. The result from a 2-D global hybrid simulation of the magnetosphere. Total magnetic field strength as well as the field lines are shown in the upper panel. Also shown are variation of field and plasma quantities across two cuts, one along the terminator and another in the outer tail region.

associated with traversal from the northern lobe through the plasmasheet boundary layer, central plasma sheet, the southern boundary layer and the lobe. These variations are similar to the modified Harris structure that has been observed recently in the magnetotail. Note that because of the large-scale flow pattern in the tail, the plasma is moving towards the magnetotail (positive Vx) even though the cut is made at the earth side of the X-line. This flow pattern reverses and becomes earthward at X ~ 900 reaching its maximum value of ~ 400 km/s at the inner edge of the plasma sheet (X ~ 600) where plasma begins to move along the dipolar field lines to both southern and northern high latitude regions.

As demonstrated above, these simulations offer an unprecedented opportunity to investigate the global magnetospheric physics on ion spatial and temporal scales. In spite of the wealth of new physics that we have been able to uncover through these simulations, much remains to be done. We look forward to the coming year to tackle many of the remaining magnetospheric issues that are yet to be resolved.